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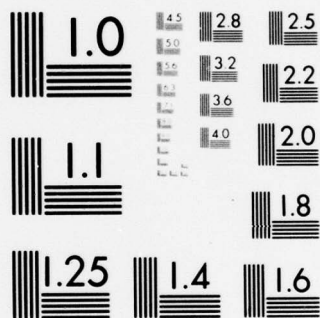UNCLASSIFIED   ARBRL-ME-02889   SBIE-AD-E430 186   NL

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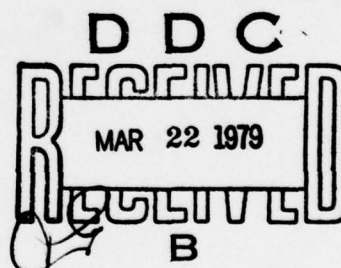
MEMORANDUM REPORT ARBRL-MR-02889

SENSITIVITY OF BURNING RATE TO INITIAL TEMPERATURE FOR A BINARY MAGNESIUM-SODIUM NITRATE MIX

Richard C. Strittmater
Hughes E. Holmes
J. Richard Ward

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19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Pyrotechnics   Combustion Models
Magnesium
Sodium Nitrate
Burning Rate
Temperature Coefficient

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)* (meg)

The temperature sensitivity of the burning rate of a mixture of magnesium and sodium nitrate (60/40 by weight) was determined at 0.1 and 1.0 MPa. The temperature sensitivity was 0.0021K^{-1} and 0.0028K^{-1} at 0.1 MPa and 1.0 MPa, respectively. A standard JANNAF composite propellant illustrated the same trend in temperature sensitivity with increasing pressure leading one to suggest the models used for composite propellant combustion are the starting point for modeling pyrotechnic combustion.
(CONT'D)

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20. Abstract (Cont'd):

Analysis of various combustion models suggests the dependence of temperature sensitivity with initial temperature as an additional tool to determine the capability of various models to describe combustion. At present the temperature sensitivity is assumed to be independent of initial temperature; experiments need to be performed over large temperature intervals in order to test this hypothesis. Pyrotechnics offer an attractive test case, since the initial temperature of a pyrotechnic can be raised to nearly 1000K before decomposition of the oxidizer or phase changes take place.

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I. INTRODUCTION

Pyrotechnics are used in a wide range of military applications, all of which depend on the controlled ignition and combustion of a pyrotechnic mix. The Engineering Design Handbook Series on Military Pyrotechnics reviews the range of effects from a burning pyrotechnic that are of military use[1]. These effects include production of heat (incendiary rounds), production of light (tracers and illuminating shells) and production of smoke (smoke grenades and smoke rounds). Pyrotechnics are also used as solid propellant igniters and primers. A novel role of pyrotechnics is to increase the range or decrease the time-of-flight of projectiles by reducing base drag[2,3].

Despite the wide role of pyrotechnics in munitions, investigations of the combustion and ignition of these substances have lagged behind similar work on composite solid propellants and homogeneous propellants. The Engineering Design Handbook on Theory and Application of Pyrotechnics[4] illustrates the gap between propellant combustion modeling and pyrotechnic combustion modeling.

In an effort to begin closing the gap between pyrotechnics and propellant combustion, an experimental program is underway to obtain burning rate data on pyrotechnic mixes. This report discusses measurements of the temperature sensitivity of the burning rate of a mixture (60/40 by weight) of magnesium and sodium nitrate. The organic binder normally found in pyrotechnic mixes was deleted in the hope of simplifying modeling efforts.

The desire to examine temperature sensitivity was prompted by work on modeling composite propellant combustion. A 1972 JANNAF workshop[5]

1.   "Military Pyrotechnics Series, Part Four, Design of Ammunition for Pyrotechnic Effects", AMC Pamphlet AMCP 706-188, March 1974.

2.   J.R. Ward, F.P. Baltakis, and S.W. Pronchick, "Wind Tunnel Study of Base Drag Reduction by Combustion of Pyrotechnics", BRL Report No. 1745, October 1974.   (AD #B000431L)

3.   K. Anderson, N.E. Gunners, and R. Hellgren, "Swedish Base Bleed - Increasing the Range of Artillery Projectiles Through Base Flow", Propellants and Explosives, 1, pp. 69-73 (1976).

4.   "Military Pyrotechnic Series, Part One, Theory and Application", AMC Pamphlet AMCP 706-185, April 1967.

5.   L. Caveny, "Workshop Report on Temperature and Pressure Sensitivity of Burning Rates", Proceedings of the Ninth JANNAF Combustion Meeting, Volume II, CPIA Publication 231, December 1972.

concluded that the ability of various models to predict temperature sensitivity may serve to validate such models better than the conventional prediction of burning rate vs pressure. This was demonstrated recently by Condon, Renie, and Osborn[6] who used prediction of temperature sensitivity to illustrate the superiority of the petite ensemble model for modeling composite propellant combustion.

II. EXPERIMENTAL PROCEDURES AND APPARATUS

A low pressure combustion chamber was used to conduct propellant burning rate studies as a function of initial temperature and pressure. A schematic of the chamber, heat exchanger and auxilliary apparatus is shown in Figure 1. The chamber was chosen to accommodate the burning of the pyrotechnic samples used in this study without increasing the initial pressure of 0.1 MPa of nitrogen more than ten percent. The volume of the chamber is 0.08 cubic meter and has a maximum operating pressure of 1 MPa. The nitrogen was circulated along the sides of the propellant sample, as shown in Figure 1, to inhibit flame spread. The propellant holder was machined from aluminum because of its high thermal conductivity. Both alcohol and water were used as the temperature conditioning fluid.

The samples were prepared in the following way. A mixture of forty percent magnesium and sixty percent sodium nitrate was poured into a mold and pressed to a pressure of 345 MPa with a hydraulic press. The sample was removed from the press and its density determined. The sample was then placed in a clamping apparatus that positioned it at the proper angle for drilling three holes (#80 drill) for receiving thermocouples. Chromel-Alumel thermocouples made of 0.05mm diameter wires were inserted into the holes. The thermocouples were used to measure the initial temperature of the propellant and the time of transit of the combustion zone. The temperature profile measured by the thermocouples could also be used for qualitative impressions of temperatures at various points in the combustion zone. Figure 2 shows the prepared sample mounted on the holder with dimensions. After purging and filling the chamber to the desired pressure with nitrogen, the temperature was adjusted to the desired value. The sample was ignited and the temperatures were recorded on a Honeywell Visicorder.

III. RESULTS AND DISCUSSION

Twenty-nine samples were prepared and burned. A large variation in burning rate was detected which depended on the density of the sample. The theoretical density of forty percent magnesium and sixty percent sodium nitrate is 2.02 grams per cubic centimeter. Only samples

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6. J.A. Condon, J.P. Renie, and J.R. Osborn, "Temperature Sensitivity of Propellant Burning Rates", Combustion and Flame, 30, pp. 267-276 (1977).
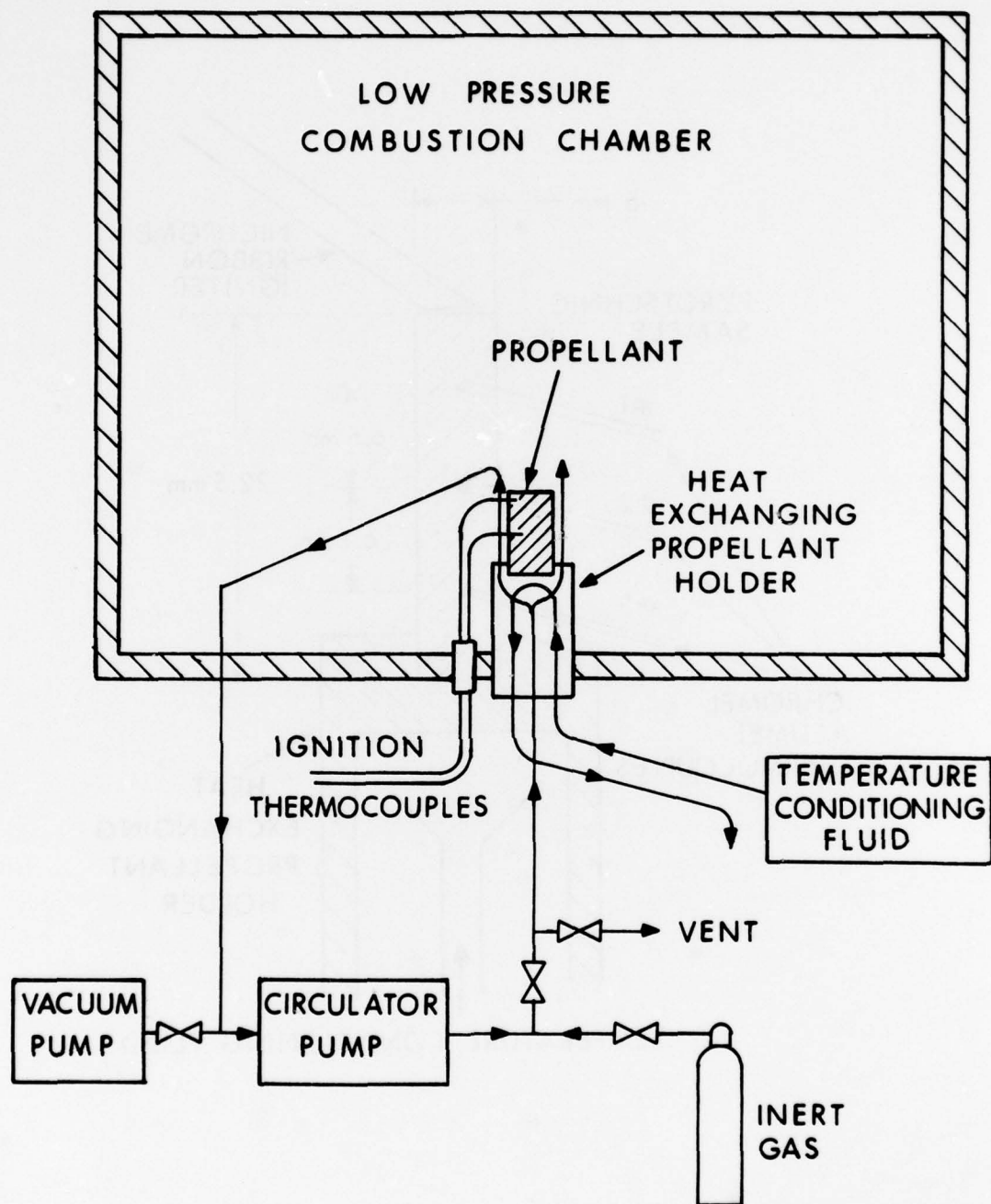
Figure 1. Schematic of System Used to Conduct Combustion Studies
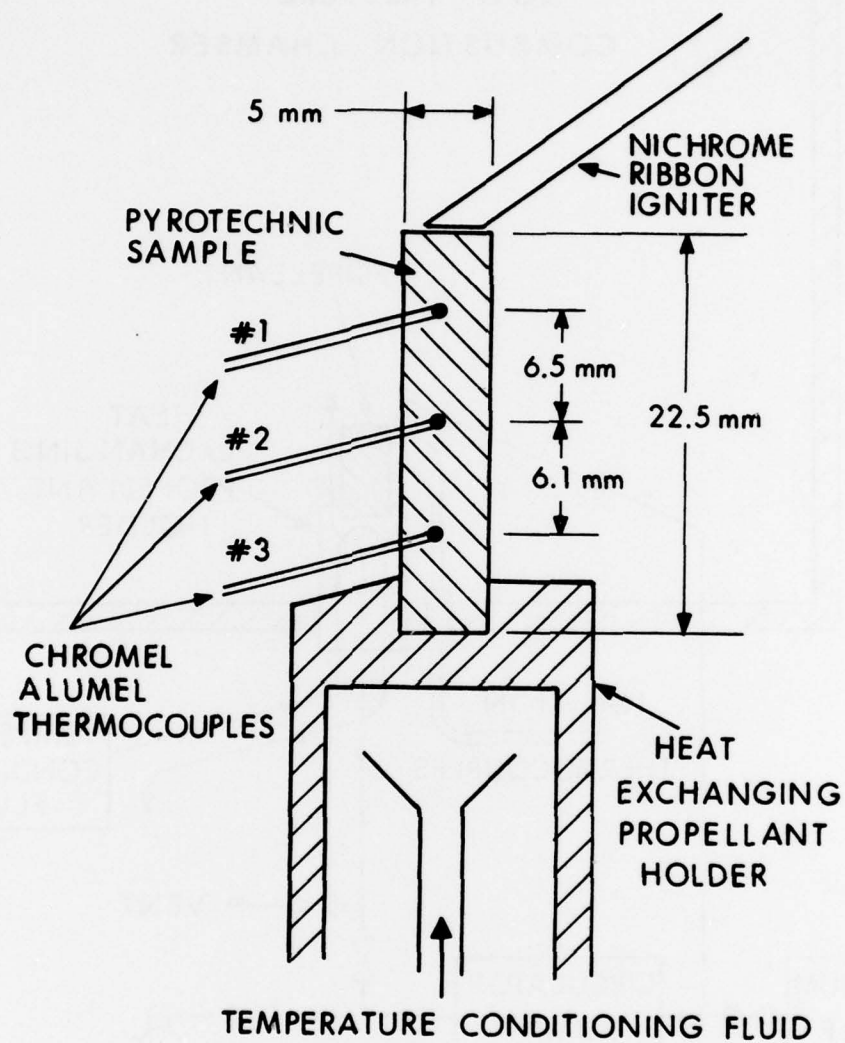to Determine Initial Temperature Sensitivity of
Burning Rate

Figure 2. Schematic of Sample Positioned on Heat Exchanger

whose densities were between 1.9 and 2.02 grams per cubic centimeter burned in a fairly reproducible manner, so only firings of samples in this density range were used in the analysis.

A copy of a typical record from the Visicorder illustrating the response of the three thermocouples is shown in Figure 3. The burning rate was determined from the time intervals bounded by the sharp increases in temperature seen in Figure 3. Table I summarizes the burning rates measured in this set of experiments. The reproducibility of the burning rates measured at each thermocouple interval is taken as evidence of uniform burning for a given run. In a number of cases, thermocouple 2 or thermocouple 3 failed to register; the data from those runs which gave burning rates in agreement with the rates in the runs with uniform burning are also included in Table I. The burning rates chosen for further analysis are taken from the time interval between thermocouples one and three except for the runs 8, 10, and 24, in which thermocouple three failed to function.

The temperature sensitivity at constant pressure is defined as the following

$$\sigma = \frac{\partial(\ln r)}{\partial T_o} \bigg|_p \quad , \tag{1}$$

where

σ = temperature sensitivity, K^{-1}

r = burning rate, mm/s

T_o = initial temperature, K.

For the mixture of magnesium and sodium nitrate under study, the plot of ln r vs T_o is shown in Figure 4. The straight line determined from a linear least-squares fit to the data is also shown in Figure 4. The values of σ determined from the least-squares analysis are 0.0021 K^{-1} and 0.0028 K^{-1} at 0.1 and 1.0 MPa, respectively. The standard estimate of error determined from the least-squares analysis is 1.5 mm/s and 1.3 mm/s at 0.1 and 1.0 MPa respectively. All the experimental points fall within the standard estimate of error.

The values of σ for the pyrotechnics mix are similar to the temperature sensitivities measured by Condon and co-workers. At 1.0 MPa they report a σ of 0.002 K^{-1} for the composite propellant in comparison to the value of 0.003 K^{-1} estimated from the few runs at the higher pressure for the pyrotechnic mix. The temperature sensitivity of the composite propellant decreases as the pressure is reduced, which is the same trend seen for the pyrotechnic mix. This trend in temperature sensitivity vs pressure reinforces one's intuition that composite propellant combustion and pyrotechnic combustion are similar, and one should use the composite propellant combustion models Condon found

TEST #9 — 1 MPa N_2 — INITIAL TEMPERATURES 280 TO 282 K

FLAME TEMPERATURE

282 K
281 K
280 K

|← 0.05 s →|

TIME ——→

TEMPERATURE

Figure 3. Copy of Visicorder Record Showing Response of Thermocouples

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TABLE I. Summary of Burning Rate Measurements

Run	T_o, K	P, MPa	ρ, g/cm^3	Δt_1, s	Δt_2, s	Δt_{13}, s	r_1, mm/s	r_2, mm/s	r, mm/s [a]
22	293	0.10	1.95	0.32	0.32	0.64	20	19	20
25	293	.10	1.99	.37	.34	.71	18	18	18
29	324	.10	1.92	.31	.30	.61	21	20	21
28	324	.10	1.96	b	b	.62	b	b	20
24	350	.10	2.02	.30	c	c	22	c	22
23	353	.10	1.97	.31	.30	.61	21	20	21
19	355	.10	1.98	.30	.28	.58	22	22	22
9	281	1.0	1.91	.31	.28	.59	21	22	21
7	282	1.0	1.98	b	b	.58	b	b	22
8	282	1.0	2.01	.31	c	c	21	c	21
10	348	1.0	1.97	.26	c	c	25	c	25
6	349	1.0	1.95	.26	.23	.49	25	26	26

a – Burning rate for each run determined from Δt_{13} except for runs in which thermocouple three failed.

b – No data from thermocouple two.

c – No data from thermocouple three.

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Figure 4. Burning Rate vs Initial Temperature at 0.1 MPa and 1.0 MPa

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predicted the temperature sensitivity best. The two models were the petite ensemble model[7] and the modified Beckstead, Derr, and Price (BDP) model[8], although Condon and co-workers found the petite ensemble model predicted burning rate vs pressure closer to experimental values then did the modified BDP model.

Another way to use temperature sensitivity measurements is to examine the dependence of σ with initial temperature.[13] Many of the theories of steady combustion[9-12] yield an expression[13] for the sensitivity of the burning rate to initial temperature of the form

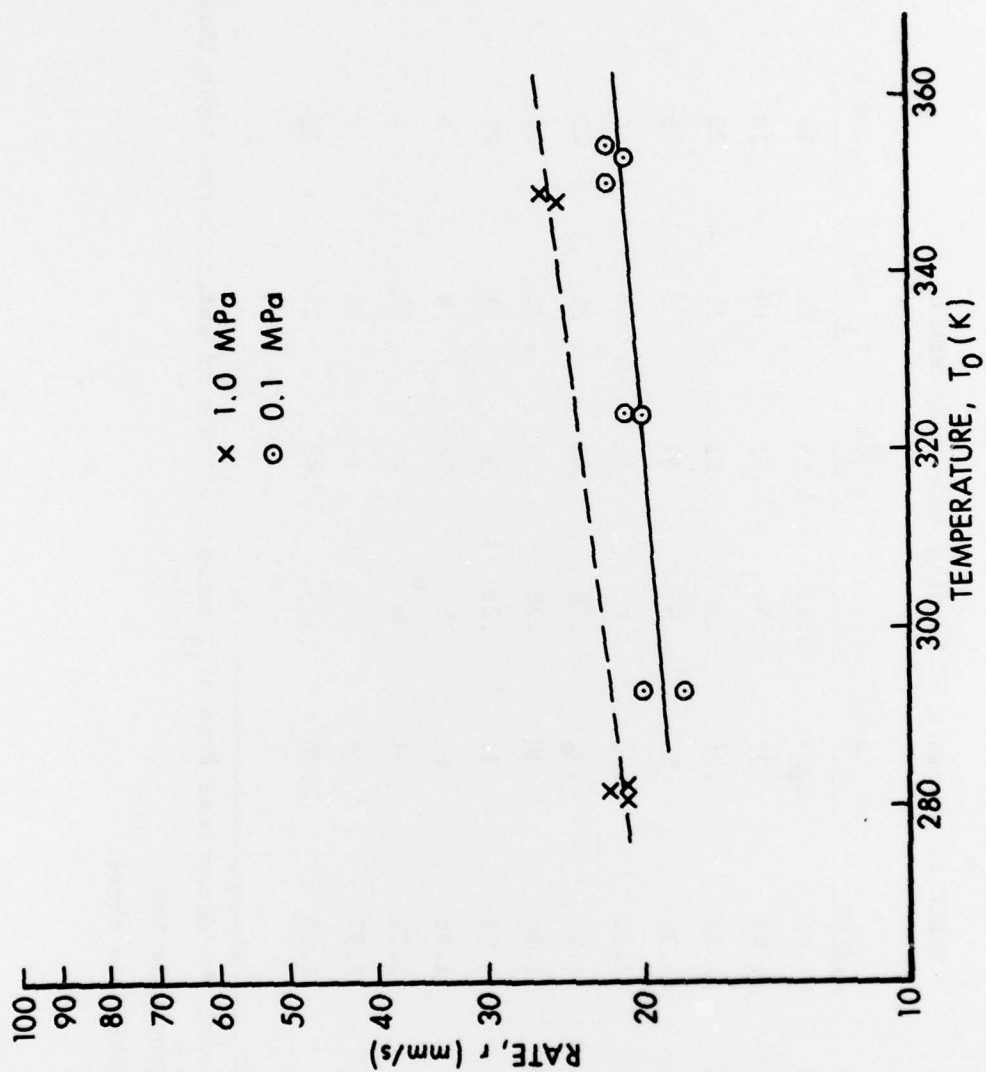$$\sigma = \frac{K_1}{(Q/C_p + T_o)} + \frac{EK_2}{2R(Q/C_p + T_o)^2} \quad , \tag{2}$$

where

σ = temperature sensitivity, K^{-1}
Q = heat of reaction, J/g
C_p = specific heat, J/g-K
E = activation energy, J/mole
R = gas constant, J/mole-K
T_o = initial temperature, K
K_1 and K_2 = dimensionless constants which range in value from 1 to 5 for K_1 and from 1/2 to 1 for K_2.

7. R.L. Glick and J.A. Condon, "Statistical Analysis of Polydisperse Heterogeneous Propellant Combustion - Steady-State", Proceedings of the Thirteenth JANNAF Combustion Meeting, CPIA Publication 281, December 1976.

8. M.W. Beckstead, R.L. Derr, and C.F. Price, "A Model of Composite Solid Propellant Combustion Based on Multiple Flames", AIAAJ, 8, pp. 2200-2207 (1970).

9. R.G. Parr and B.L. Crawford, "A Physical Theory of Burning of Double-Base Rocket Propellants", J. Physical Chem., 54, p. 929 (1950).

10. R.L. Coates, "An Analysis of a Simplified Laminar Flame Theory for Solid Propellant Combustion", Combustion Science and Technology, 4, p. 1 (1971).

11. M.W. Beckstead and N.S. Cohen, "Temperature and Pressure Sensitivity of Composite Propellants", Proceedings of the Seventh JANNAF Combustion Conference, CPIA Publication 204, February 1971.

12. T. von Karman and G. Millan, "The Thermal Theory of Constant Pressure Deflagration", Anniversary Volume on Applied Mechanics, Dedicated to C.B. Biezeno, pp. 59-69, N.V. Technische Uitgevery: H. Stam, (Holland) 1953.

13. R.C. Strittmater, H.E. Holmes, and E. Wineholt, "The Temperature Sensitivity of Gun Propellants", BRL Memorandum Report No. 2593, February 1976. (AD #A022200)

Equation (2) shows that σ should be reduced as the initial temperature increases. Since σ is the slope of a plot of ln r $\underline{vs}$ T_O, one should see curvature downward of such a plot at the higher values of T_O. If the ln r $\underline{vs}$ T_O is curved, then this deviation from the usually assumed straight line may be useful as a guide to testing the suitability of a model. To date plots of σ $\underline{vs}$ P have been used to discriminate between different models as Condon and his collaborators did. Pyrotechnics, such as magnesium and sodium nitrate, offer a chance to see if a plot of σ $\underline{vs}$ T_O could serve to distinguish models, since the initial temperature can be raised to nearly 1000K before decomposition or phase changes occur in the condensed phase in comparison to conventional propellants where the decomposition can take place at 500-600K. For the data gathered in this report, ln r $\underline{vs}$ T_O may be represented by a straight line; future experiments will be done at higher values of initial temperature to see if curvature of the ln r $\underline{vs}$ T_o line can be observed.

IV. CONCLUSIONS

1. The temperature sensitivity of a 60/40 by weight mixture of magnesium and sodium nitrate was determined to be 0.0021 K^{-1} at 0.1 MPa, and 0.0028 K^{-1} at 1.0 MPa.

2. The trend for the pyrotechnics temperature sensitivity to increase with pressure is similar to the dependence of composite propellant temperature sensitivity with pressure. This analogy suggest combustion models applicable to composite propellants should be the starting point for modeling pyrotechnic combustion.

3. At present the dependence of temperature sensitivity with pressure is used to determine the capability of combustion models to describe propellant burning. Another way to test combustion models with information from burning rate at various initial temperatures is to examine the dependence of temperature sensitivity with initial temperature rather than pressure. The change in temperature sensitivity with temperature will be reflected by curvature in the plot of ln r $\underline{vs}$ T_O. Measurements of temperature sensitivity are needed over a larger temperature range than is presently employed.

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